Energy for Sustainable Development 27 (2015) 73–83

Contents lists available at ScienceDirect

Energy for Sustainable Development

The influence of users' behavior on biogas production from low cost tubular digesters: A technical and socio-cultural field analysis

J. Martí-Herrero [a,b,*], M. Ceron [c], R. Garcia [d], L. Pracejus [e], R. Alvarez [f], X. Cipriano [a]

[a] Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), Building Energy and Environment Group, Edifici GAIA (TR14), C/Rambla Sant Nebridi 22, 08222, Terrassa, Barcelona, Spain
[b] Instituto Nacional de Eficiencia Energética y Energías Renovables (INER), 6 de Diciembre N33-32, Quito, Ecuador
[c] Institute for Technologies in the Tropics (ITT), Cologne University of Applied Sciences,Betzdorfer Straße 2, 50679 Köln (Deutz), Germany
[d] Ingenieria de Petroleo, Gas y Energías, Universidad del Valle, C| Guillermina Martínez s/n, Tiquipaya, Bolivia
[e] University of Natural Resources and Applied Life Sciences Vienna (BOKU), Gregor-Mendel-Straße 33, 1180 Vienna, Austria
[f] IIDEPROQ, UMSA, Plaza del Obelisco 1175, La Paz, Bolivia

ARTICLE INFO

Article history:
Received 15 April 2014
Revised 5 February 2015
Accepted 5 May 2015
Available online xxxx

Keywords:
Biogas production
Bioslurry
Cold climate
Household low cost tubular digester
Socio-cultural technical analysis

ABSTRACT

The aim of this paper is to understand the influence of the user behavior on tubular digesters performance, through a technical and a social approach in the Bolivian context. Fifteen domestic digesters were evaluated, from which 6 were installed in the Altiplano and other 6 in the Andean Valleys. Data about slurry temperature, feedstock and biogas quality were collected from these 12 digesters, while daily biogas production and feeding pattern were also monitored from further three digesters in the valleys. Because of changes in user behavior along the monitoring period and particular characteristics of the digesters monitored, 5 complete patterns of biogas production and digester management were established. Furthermore, the results of a socio-cultural study with Andean families about the perception of poverty, their needs and the role played by digesters in their expectations in improving life quality, are correlated to the obtained technical data. The technical evaluation shows how the digester management seems to have a seasonal performance throughout the year according to the agricultural calendar. This means that families are more interested in using bioslurry in crops and agricultural improvements than in the use of biogas. The Bolivian government subsidy on liquefied gas seems to be one of the key issues to understand these results. Finally, data also reveals how the thermal behavior of tubular digesters adapted to cold climate that use a passive solar design, is similar to the thermal behavior of valley digesters, and therefore intends to add the same passive heating techniques for warm and tropical climates, to increase slurry temperatures and achieve a higher biogas production.

Introduction

According to a special report by the *International Energy Agency* in, 2012 more than 1.3 billion people live without access to electricity and more than 2.6 billion use wood, charcoal or animal dung for their daily cooking. As modern energy is seen as a key element to reduce poverty and enable human development, various international programs now focus on the distribution of access to appropriate modern ways of energy worldwide. One of these promising technologies is the household digester to provide biogas for cooking from the anaerobic digestion of fresh manure. In recent years many National Biogas Programs (NBP) were developed in South Asia, India and Africa and more than 45 million systems were installed (Bond and Templeton, 2011; Chen et al., 2012; Ghimire, 2013). This massification strategy is now being transferred to Nicaragua as well.

Since 1992, when the first NBP started in Nepal, all the upcoming programs mainly focused on biogas production, in order to replace wood as a cooking fuel, improving family health through a smoke free indoor environment, reducing deforestation and water contamination (Bond and Templeton, 2011; Chen et al., 2012; Ghimire, 2013; Mwirigi et al., 2009; Walekhwa et al., 2009). Just as recent as the Ghanaian NBP (Arthur et al., 2011) the digestate (which is also known as bioslurry, especially when referring to the fertilizer or when the potential wants to be highlighted) is appreciated as the main product of anaerobic digestion. In the last years, African and South American experiences have also highlighted the importance of bioslurry as a fertilizer which improves crop productivity (Garfí et al., 2011a), as well as protection and recovery from frost damage (Martí-Herrero et al., 2014a). In 2013 the FAO published a review about bioslurry and the opportunity to use it with the suggestive title of “Bioslurry = brown gold?” (de Groot and Bogdanski, 2013), similar to other recent review publications like “Bioslurry: a supreme fertilizer” (Warnars and Oppenoorth, 2014)

* Corresponding author at: Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), Building Energy and Environment Group, Edifici GAIA (TR14), C/Rambla Sant Nebridi 22, 08222, Terrassa, Barcelona, Spain.
E-mail address: jaimemarti@cimne.upc.edu (J. Martí-Herrero).
URL:E-mail addresses:E-mail address: http://www.cimne.upc.edu (J. Martí-Herrero).

http://dx.doi.org/10.1016/j.esd.2015.05.003
0973-0826/

and that from Bonten et al. (2014). Therefore, digesters in comparison with other most popular renewable energy technologies, benefit the economic development and the mitigation of climate change in rural areas, by producing energy, increasing local food production and acting as an efficient waste and water treatment system.

There are plenty socio-economic and technical analyses published about household digesters, focused on the fixed dome and floating drum model users, which are the most widespread models in the world, but less attention has been given to the tubular digesters users, which are mainly implemented in Latin America. Most of these investigations have an *etic* point of view, where the "*etic* approach" is focused from the researcher observations, categories, explanations, and interpretations, instead of being focused from the point of view of the target people from the study (Kottak, 2006). For example, Walekhwa et al. (2009) analyzes factors affecting the adoption of biogas energy in Uganda, according to age and gender, household income and size, and number of cattle owned. Walekhwa et al. conclude some policy recommendations, but no information is given outside of these parameters about the opinion of the potential biogas users. Mwirigi et al. (2009) do a similar exercise for Kenya, coming up with the statement "while a farmer's socio-economic status significantly influenced the decision to adopt the technology, it did not influence the sustainability of the constructed plants", when analyzing the answers from the users of different digester models about biogas production, repairs, and appropriation. Van Groenendaal and Gehua (2010) realized a standard economic feasibility analysis, without considering the users' point of view. They explain how the impacts of bio-digesters on the farm economy "are often small if not non-existent", but "contribute considerably to a more convenient lifestyle and an improved indoor environment". Furthermore, Yiridoe et al. (2009) extended the standard economic feasibility analysis by including key nonmarket co-benefits from biogas energy production, trying to consider other no measurable parameters. These benefits, among others, include the reduction on manure odor, toxicity and pathogen spreading, weed seed germination and expansion, water contamination and greenhouse gases emission, but again the opinion and other possible co-benefits that users may identify, are not considered in the study. Garfí et al. (2012)) reported technical, environmental and socio-economic impacts of low cost tubular digesters in rural communities of the Peruvian Andes. The survey that was realized with 12 families, who were biogas users, was structured as a close questionnaire that did not permit gathering the free opinion of the users, it only considered the parameters important for researchers. Later on, Garfí et al. (2014) compare the fixed dome and plastic tubular digester in terms of biogas production, costs and environmental impact, using the life cycle assessment methodology. Nzila et al. (2012) also present a multi-criteria analysis considering technical, economic and environmental sustainability dimensions for different digester models. Arthur et al. (2011) show the actual biogas technology utilization, and the potential benefits, prospects and challenges in Ghana. Ghimire (2013) reports the results from different NBPs in Asia and Africa, providing the number of digesters installed through the multi-actor program methodology, recommendations and lessons learned. Similar studies were conducted by Martí-Herrero et al. (2014a) in Bolivia, Chen et al. (2012) in China or Bond and Templeton (2011) for the general developing world. However, the end user's opinions (also known as *emic* approach, which is opposed to the *etic* one, and consists in a description of behavior or a belief of a group of people in terms of internal elements and their functioning rather than in terms of any existing external scheme) about poverty, energy poverty and the role of digesters in their lives is hardly considered in these studies.

The core of this research is to analyze the household digesters' performance as they are used by families, and highlight the influence of the users' mindset and behavior in relation to the performance of the system. So this study combines the *emic* and the *etic* approach. In this case we evaluate 15 digesters, 6 installed in the Bolivian Altiplano (at 3800 meters above sea level, masl) and 9 in the Bolivian Andean valleys (around 2600 masl). Some of them were monitored in depth for a long period on user behavior, resulting in 5 different patterns of digester management and biogas production. At the same time, a social analysis from the users' point of view, about poverty and the role of digesters to overcome the poverty situation, will be presented. The social analysis conducted among users and non-users of digesters was carried out with Aymara indigenous families from the Bolivian highlands. Finally, how the different patterns of digesters use evolve according to the influence of government energy policy is discussed. In Bolivia, liquefied petroleum gas (LPG) has been subsided and therefore became more accessible to the rural population in the last years.

Low cost tubular digesters

Household low cost tubular digesters (Fig. 1) are the cheaper evolution of the Taiwanese 'red mud' model (Pound et al., 1981), developed by Preston and co-workers (Botero and Preston, 1987; Bui Xuan et al., 1994) at the end of the 80s. These models were adapted to the cold climate of the Andean region in Bolivia and Peru, despite only making use of a passive solar heating design (Martí-Herrero, 2007; Poggio et al., 2009). These digesters have a tubular reactor made with a double tubular polyethylene plastic layer (Lansing et al., 2008; Martí-Herrero, 2011), although, in some countries polyethylene is replaced by PVC or polyethylene geomembrane as in Mexico, Colombia, Ecuador, Costa Rica and Peru. The dimension of the reactor can vary from 3 to 8 m of circumference (Martí-Herrero, 2011). A detailed design methodology can be found in Martí-Herrero and Cipriano (2012). These digesters are semi-buried in a trench, leaving the biogas bell visible from outside. The household digester in Bolivia has been designed to be fed every day with 20 kg of fresh manure and 60 l of water (1:3 manure:water ratio), producing 0.7 to 0.8 m^3 of biogas per day and 80 l of bioslurry, independently of the climatic region, as for each climate (cold-altiplano, warm-valleys and tropical-tropics) a specific design is developed to achieve the same results (Martí-Herrero, 2008). The Organic Load Rate (OLR), Specific Biogas Production (SBP), Biogas Production Rate (BPR) and the Hydraulic Retention Time (HRT) values obtained from the monitoring of low cost tubular digesters fed with cow manure, adapted to normal conditions from Martí-Herrero et al. (2014b), are: 0.34 kg_{SV}/m^3/day, 0.335 m^3/kg_{SV}, 0.11 m^3/m^3/day and 90 days (Garfí et al., 2011b) and also 0.22 kg_{SV}/m^3/day, 0.30 m^3/kg_{SV}, 0.065 m^3/m^3/day and 90 days (Ferrer et al., 2011) at valley conditions. While for cold climate conditions the values are 0.26 kg_{SV}/m^3/day, 0.23 m^3/kg_{SV}, 0.06 m^3/m^3/day and 124 days (Martí-Herrero et al., 2014b). In cold climates, such as in the highlands of the Altiplano, the tubular digester is insulated from the ground and integrated into a greenhouse, composed by thermally massive adobe walls covered with a transparent plastic sheet.

Digester characterization methodology

Four parameters are considered the most relevant to characterize a digester, two of them are related to the operation and the other two parameters to the performance of the system. The Organic Load Rate (OLR) [kg_{sv}/m^3/day], which is related to the amount of organic matter (kilograms of volatile solids, VS) charged every day to the digester per m^3 of useful volume of digester, and the Hydraulic Retention Time (HRT) [day], that is calculated dividing the liquid or useful volume of the digester by the mean volume loaded every day, are both operational parameters. When a digester is designed, the operational parameters (OLR and HRT) are fixed for a specific feeding pattern, but when the user changes this pattern, the real OLR and HRT values of the system change as well.

The digesters fed with cow manure considered in this survey were designed for cold climate regions with a reference OLR of 0.37 kg_{sv}/m^3/day, an HRT of 81 days, and with a liquid digester volume of 6.47 m^3; for valleys with an OLR of 0.66 kg_{sv}/m^3/day, an HRT of 46 days and 3.65 m^3 of liquid volume. In the case of digesters fed with pig manure in the valleys the reference OLR is 0.58 kg_{sv}/m^3/day, the HRT of 65 days and the liquid volume is 6.47 m^3, similar to the highland

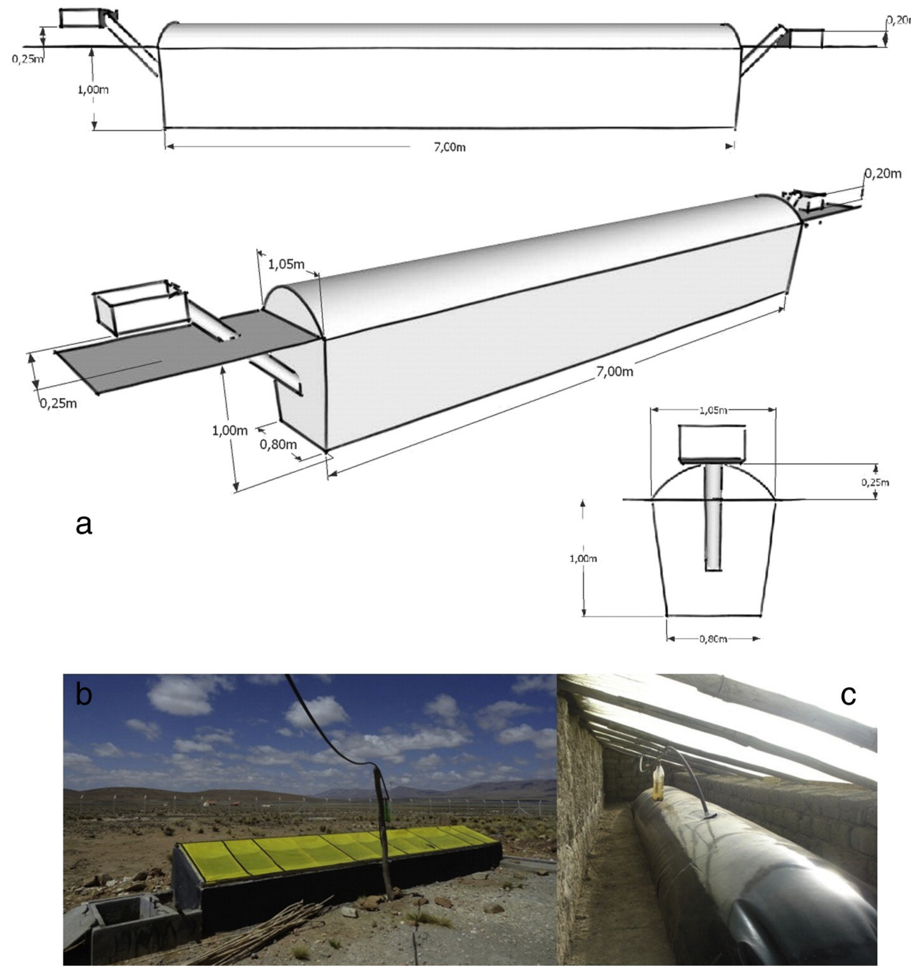

Fig. 1. a) Design of a household low cost tubular digester. b) Outside view of a low cost tubular digesters adapted to cold climate inside a greenhouse with adobe walls. c) Inside view (Martí-Herrero et al., 2014a).

digester which is fed with cow manure. In some cases in the valleys two digesters are connected in series, resulting in a double amount of useful liquid volume, though OLR and HRT keep the same, since the amount of manure to be fed is also twice as much. The mean real OLR and HRT during the monitoring period are estimated considering the mean daily influent of the digester, the days that the user fed the digester, the amount of mixture of water and manure employed and its characteristics.

The Specific Biogas Production (SBP) [m^3/kg_{sv}], which is related to the efficiency of the anaerobic digestion process (measured in m^3 of biogas produced per kg_{SV}), and the Biogas Production Rate (BPR) [m^3/m^3/day], which is related to the general efficiency of the digester and answers this question: How much biogas is produced in relation to the useful volume of the digester?, where BPR = OLR * SBP, are both considered performance parameters.

To understand the circumstance where the digester is working, it is necessary to know the outdoor as well as the working temperature inside of the system, and if no active heating device is employed, as it is in this case. It is also important to know the pH values of water, influent and effluent; the Total Solids (TS) [kg_{TS}/kg] and SV from the feedstock, the influent and the effluent, to understand the performance of the digester. The biogas composition (%CH_4 and %CO_2) is also necessary for the potential energy use calculation. These parameters can be identified through a simple visit to the household digester, collecting and analyzing samples of feedstock, influent, bioslurry, biogas and measuring the pH and temperatures where it corresponds.

However, in order to diagnose the OLR, HRT, SBP and BPR, a monitoring period is needed. For this purpose, the installation of a gas meter to monitor the biogas production is required, as well as a control of the amount and frequency of manure and water loaded to the digester, in order to determine the OLR and HRT. The gas meter is easy to install and does not represent an inconvenience for the user, but determining how many days the user loads the digester and the amount of water and manure has a social component that must be taken into consideration. Since the biogas production to be monitored is related to the daily schedule of load of the digester, the same load frequency of the previous days and weeks must be kept during this period. Often, when the monitoring period starts, users tend to change the normal load frequency in order to achieve better BPR values at the evaluation. On the other hand, not to disturb users' usual behavior is essential to obtain real values of OLR, HRT, SBP and BPR.

In the present research, gas production and load frequency of 3 household digesters situated in the valleys were intensely monitored throughout 6 months. Further 12 digesters were partially monitored for around 2 weeks to 2 months, meaning that load frequency has not been registered (6 of them are situated in the highlands and the other 6 in the valleys). The main design, operational and performance parameters of these 15 digesters are presented in Table 3 of the Results and discussion section.

Partial monitoring of household digesters

Partial monitored digesters are those where samples of water, feedstock, influent, bioslurry and biogas for characterization purposes were collected once. Biogas production, load frequency and amount of load have not been collected, hence, the OLR, HRT, SBP and BPR of the digesters cannot be characterized in these cases. The monitoring of the slurry temperature was realized in five times during a period of time that varies from 2 weeks to 2 months. Six of the partial monitored digesters were installed in the highlands, above 3800 masl (Dh1–Dh6), and are therefore considered as cold climate digesters. The remaining six were situated in the valleys at around 2600 msnm (Dv7–Dv12) where the weather is warmer.

Intense monitoring of household digesters

Intense monitored digesters are those that were monitored during more than 6 months, recording every day if the user loads the digester; collecting the biogas production almost every day and measuring once a month the usual amount of manure and water used for the influent. Also, the slurry temperature was monitored for two of these digesters during 2 weeks at one digester and further 7 months at another digester. Other relevant parameters to characterize these digesters were the collection of water, feedstock, influent and bioslurry characteristics. Three household low cost tubular digesters, that do not require of active mixing or heating devices, were intensely monitored in the Cochabamba valley (2600 masl). Two of them (Dv13 and Dv15) were a two stage systems, that consist in two connected tubular digesters installed in series, while the third one was a single digester (Dv14). Dv15 was loaded with pig manure and measurements of the biogas production were collected for each of its stages. This permits to examine and understand the behavior of two different HRT functioning in the same system. In contrast, Dv13 and Dv14, which were loaded with cow manure, obtained just a single biogas production profile for the whole system in each case. Dv14 had two different frequencies of load schedule, while Dv13 had only one. Since these three digesters were operated in the valley region and there were no intense monitored digesters in the highlands, data reported by Martí-Herrero et al. (2014b) from an experimental digester (D90) intensely monitored in the highlands, is also considered in the Results and discussion section, in order to compare the tubular digesters performance in both regions (valleys and highland/cold climate).

Analytical analysis

Biogas production has been recorded almost every day in situ, using a commercial low pressure diaphragm gas meter (G2.5 Metrix). Biogas samples have been collected in 10 ml syringes and introduced in plastic bottles, which contain water (pH 2), and were sealed to avoid the dilution of carbon dioxide CO_2 in water. These samples were correlated to those taken with Tedlar bags giving 1% difference in the composition of biogas. The methane and carbon dioxide concentrations have been determined using a gas chromatograph (Shimadzu Model GC14B, Japan) equipped with a thermal conductivity detector (TCD) and a Carboxen-1010 plot Capillary column 30 m × 0.53 mm ID (Supelco, USA). The injector, detector and oven temperatures are fixed at 130, 200, and 100 °C, respectively. Helium has served as the carrier gas at a pressure of 300 kPa.

For the characterization of the influent and effluent, three samples have been collected once the digester had a stable performance. Total solids (TS), volatile solids (VS) and pH were determined according to standard methods (Clesceri et al., 2000). The total solids (TS) content was determined after heating (105 °C for 1 h), cooling, desiccating, and weighing procedures that were repeated until the weight change was less than 4%. Volatile solids were determined by ignition of the residue produced in TS analysis to constant weight in a muffle furnace at a temperature of 550 °C.

Slurry temperatures were monitored using temperature data logger (HOBO pendant), inserted 1 m inside the digester through the exit pipe.

Social analysis methodology

In a parallel fieldwork to the digesters activity, a socio-cultural analysis has been carried out with 8 indigenous Aymara families in the Altiplano of Bolivia. Six of these families were selected as digester users while two of them were not, in order to compare their perception and the impact of the system in the family's daily lives. Four of the six families that installed a digester still use it, while two of them do not any more: one digester was destroyed by extreme weather conditions (hailstorm); and in the second case the family member who was responsible for the digester migrated to the city (Table 1). The families were selected according to the poverty definition applied by the United Nations and defined in the *Multiple Poverty Index* (MPI). MPI criteria do not include monetary values, but focuses on health, education and various categories of living standards like access to safe drinking water, child nutrition and health care services, access to electricity, modern cooking fuels and improved sanitation facilities among others (Alkire and Santos, 2010). According to this index, a household is considered multidimensionality poor if the family is deprived in all of the six living standard criteria or in at least three of them and one criteria of the other two areas – health or education – or if the weighted indicators in which they are deprived add up to at least 33% (UNDP, 2010).

The goal of the socio-cultural field investigation was to get first hand data on how exactly the digesters and the generated biogas are used, how the families perceive the concept of "poverty", how is the impact of digesters on poverty reduction and how the families profit from these changes. Identifying the Aymara families "value system" according to how they live and judge, their goals in life, their fears and hopes for the future, was of crucial importance to start this investigation (*emic* approach). For that reason, the research methodology consisted in living with the families for various days, sharing their normal life and helping in the daily chores. There were no formal and closed interviews, and the questions were formulated along numerous kind conversations maintained with the families to ensure that answers were given honestly and as natural as possible. In the following, the results of the family's poverty analysis, according the MPI are summarized.

Education is measured in years of schooling and child school attendance. All parents that took part of this study have primary education and know how to read, write and do basic mathematics. Almost all children go to school and some even study in La Paz. Only one daughter abandoned school after 5 years to look after her younger sister and help the parents at home. According to the MPI this means that in the sector of education the majority of families are not categorized as poor, as they fulfill the minimum requirements.

Health is measured by child mortality and nutrition. The families that form part of this investigation had 62.5% cases of early child death (at least one or more in each family). The question of nutritional quality is based on quantity as well as variety of available food. While potatoes, beans, grains, milk and meat were abundant, only small amounts of fruits or vegetables are available and of scarce variety. Although none of the family members seemed undernourished, malnutrition and the lack of various vitamins and minerals cannot be excluded with certainty. Colds and stomach pains occur frequently but are usually treated traditionally with herbal teas and urine.

Living Standard is measured by access to electricity, improved sanitation, safe drinking water, flooring, cooking fuels and assets ownership. Not a single family taking part in the study has an improved sanitation system. All houses had a simple earth floor. There were no drinking

Table 1
Families considered in the socio-cultural analysis.

Number of families	8
Without digester	2
With digester	6
In use	4
Abandoned	2

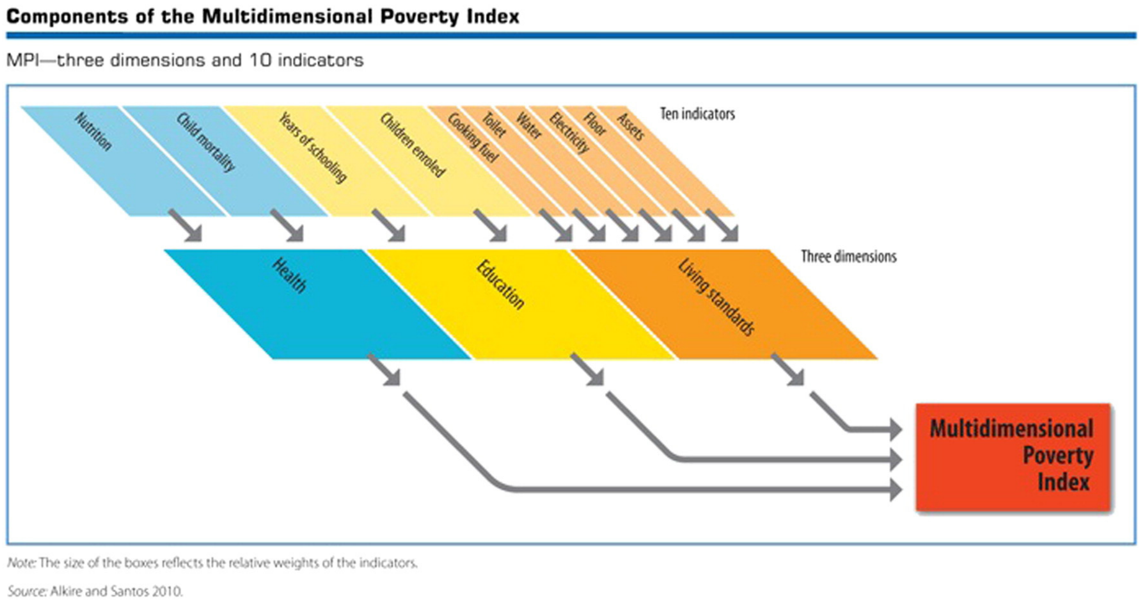

Fig. 2. Components of the *Multiple Poverty Index* (MPI) (http://hdr.undp.org/en/statistics/mpi).

water systems in the surrounding area. Water was collected from springs or ponds, and mostly boiled before drinking. Conventional electricity was only available to one of the families. Another family had a PV panel for lighting, while the remaining families used batteries for their portable radios and illuminated their houses with candles and petroleum lamps by night. The type of cooking fuel varied from liquid gas in bottles, to dry manure and wood. The use of GLP depended partly on the distance to the next accessible road. All families owned at least two radios and a mobile phone, some possess bikes; one family recently bought a camera.

Following the MPI indicators, only the issue of education (ignoring the quality) and the accessibility of varied food are sufficient in the families involved in this study. With more than half of the families having suffered early child deaths, having unsafe drinking water conditions and deficits in five (out of six) indicators of living standard, these families would be considered as multidimensional poor, according to the standards of UNDP's MPI (Fig. 2; Table 2).

Results and discussion

Water, substrate, influent and effluent characterization

In the valleys, cow manure is more humid than in the Altiplano (2% more), it has less organic matter (16% less wet weight, ww) and the families use a higher dilution of manure in water (1:3.12 in the valleys in comparison to 1:3.02 in the highlands) (Table 3). This data is similar to data reported earlier for highlands (Alvarez et al., 2006) and Andean valleys (Ferrer et al., 2011; Garfí et al., 2011b). So the mean organic matter composition of cow manure in the influent mixture is lower in valley digesters, with 2.71% VS (ww), in comparison with highland digesters, which is 3.20% VS (ww). The pH of the water to be mixed with the manure is similar in highlands (7.9) and valleys (8). The final pH values of influent and effluent are also similar in highlands (7.2 and 7.6 respectively) and in valley digesters (7.3 and 7.4, respectively).

Table 2
MPI indicators results.

	Indicator	Measurement Family is deprived if…	%Families		
			Reaching the minimum	Deprived	Could not be evaluated
Education	Years of schooling	…any household member has not completed five years of schooling	87.5%	12.5%	0%
	Child school attendance	…any school-aged child is not attending school up to class 8	62.5%	12.5%	25% [a]
Health	Child mortality	…any child has died in the family	37.5%	62.5%	0%
	Nutrition	…any adult or child is malnourished	0%	0%	100% [b]
Living standard	Electricity	…the household has no electricity	0%	100%	0%
	Improved sanitation	…the household's sanitation facility is not improved (according to MDG definition) or is shared with others	0%	100%	0%
	Safe drinking water	…the household has no access to safe drinking water (MDG definition) or safe drinking water is more than a 30 minutes-walk away (round-trip)	0%	100%	0%
	Flooring	…the household has a dirt, sand or dung floor	0%	100%	0%
	Cooking fuel	…the household cooks with dung, wood or charcoal	0%	100%	0%
	Asset ownership	…the household does not own more than one radio, TV, telephone, bike, motorbike or refrigerator nor a car or a truck	62.5%	37.5%	0%

[a] Families are childless.
[b] Could not be evaluated ecotrophologically in the scope of the socio-cultural research.

Table 3
Parameters of the digesters considered in this research.

Digester	Altitude (m)	Period	Useful Volume (m^3)	Type manure	%TS manure	%VS/TS manure	Load ratio (1:x)[1,m]	%TS load	%VS load (WW)	% TS effluent	%VS effluent (WW)	pH water	pH load	pH effluent	Tslurry (°C) [m]
Dh1	3844	May/Jun	6.47	Cow	14.96	82.45	3	3.74	3.08			7.3	6.8	7.7	
Dh2	3838	May/Jun	6.47	Cow	15.80	80.65	3	3.95	3.19			8.2	7.4	7.4	
Dh3	3831	May/Jun	6.47	Cow	11.03	85.35	3	2.76	2.35			7.5	7.2	7.8	
Dh4	3835	May/Jun	6.47	Cow	15.37	90.20	3	3.84	3.47			8.5	7.3	8.5	16.9
Dh5	3834	May/Jun	6.47	Cow	17.23	86.18	3	4.31	3.71			8.1	7.3	6.8	14.6
Dh6	3834	May/Jun	6.47	Cow	19.14	71.50	3	4.79	3.42			7.9	7.1	7.7	14.7
D90[a]	3884	Jan/Dic	0.85	Cow	17.00	76.00	3.12	4.13	3.18	2.70	2.05		7.2	7.2	16.6
Highland means					15.79	81.76	3.02	3.93	3.20			7.9	7.2	7.6	15.7
Dv7	2676	Jun/Jul	3.65	Cow	14.39	82.99	3.33	3.32	2.76			8.5	7.1	7.2	
Dv8	2663	Jun/Jul	7.3	Cow	11.76	84.56	3.25	2.77	2.34			7.8	7.0	7.6	
Dv9	2644	Jun/Jul	7.3	Cow	12.71	73.82	2.71	3.43	2.53			8.3	7.4	6.8	
Dv10	2561	Jun/Jul	3.65	Cow	16.01	81.30	3	4.00	3.25			7.7	7.4	8.7	
Dv11	2686	Jun/Jul	3.65	Cow	14.16	77.76	3	3.54	2.75			8.5	7.0	6.7	14.8
Dv12	2628	Jun/Jul	7.3	Cow	13.62	75.42	3.15	3.28	2.48			8.0	7.0	7.7	13.6
Dv13	2628	Sep/Mar	7.3	Cow	14.14	72.41	3.78	3.74	2.71	2.92	1.92	7.3	8.3	7.3	19.7
Dv14a	2682	Jan/Mar	3.65	Cow	13.83	78.32	3.41	3.14	2.46						19.7
Dv14b	2682	Apr/Jun	3.65	Cow	13.83	78.32	2.45	4.01	3.14						17
Valley mean					13.83	78.32	3.12	3.47	2.71			8.0	7.3	7.4	
Dv15a	2607	Sep/Mar	6.47	Pig	26.26	75.76	4.10	5.15	3.90	3.50	2.27	7.4	7.4	6.9	21.6
Dv15b	2607	Sep/Mar	12.9	Pig	26.26	75.76	4.10	5.15	3.90	3.08	1.91	7.4	7.4	7.0	21.6

[1] Load ratio manure:water; [2] temperature difference between slurry and ambient; [3] amount of manure employed when the digester is loaded; [4] daily mean manure loaded along the monitoring period; [5] local conditions; [6] normal conditions (760 mm Hg, 0 °C); [a]Martí-Herrero et al. (2014a); [m] mean values for the monitoring period.

The reduction in TS at the cow manure fed digester Dv13, from the influent to the effluent, is 22%, and the reduction for the VS is 29%. The pig manure fed digester Dv15a presents a reduction of TS of 32%, and a reduction of VS of 41%. When the HRT is doubled (Dv15b), the reduction of TS increases to 40% and the reduction of VS to 51%.

Feeding pattern of digesters

Different feeding patterns have been found at all families taking part in this survey, although all of them have enough water and manure for daily digesters feeding throughout the whole year. When load frequency was not collected (partial monitored digesters: Dh1–Dh6 and Dv17–Dv12), the assumption through interviews and successive visits to the users, is that the % of loading days is less than 25%. The intense monitoring study cases (Dv13, Dv14 and Dv15) show a very different pattern in load frequency, presenting profiles from 23% to 100% of total days in which the digester was fed. Dv13 is a two stage digester installed in the valleys, fed with cow manure, and is loaded 23% of the days (Fig. 4). Dv14 is a single stage digester in the valleys fed with cow manure, and during the monitoring period the user changed the load frequency from 100% to 51% of the days, so two different profiles can be observed (see Fig. 5), and will be commented later. At last Dv15 is a two stage digester installed in the valleys, fed with pig manure almost every day (94%), its load frequency is presented in Fig. 6. These feeding pattern discrepancies between the intense monitoring digesters can be explained by the need of biogas and/or bioslurry according to the availability of other cooking fuels (wood, dry manure or liquid petroleum gas).

Thermal performance

Fig. 3 presents data obtained from four digesters that were monitored by regions (highland and valleys), while the mean values can be found in Table 3. At the highland all the digesters have very similar slurry temperature independently of the weather season; the mean value is 15.7 °C with a standard deviation of 1.2 °C. During the summer season D90 and Dh4 slurry temperatures are 16.6 °C and 16.9 °C respectively. While during the beginning of the winter, where almost all of the nights freeze, the temperatures drop to 14.6 and 14.7 °C for Dh5 and Dh6. Perrigault et al. (2012) report a low cost tubular digester adapted to cold climate that reaches 24.5 °C of slurry temperature, increasing with 8.4 °C the mean ambient temperature. This data is very similar to the four cases of the present study where the slurry temperature is 7.8 to 8.3 °C above the mean temperature, indicating a similar performance for all the highland low cost tubular digesters adapted to cold climate.

The slurry temperature of valley digesters has a greater annual amplitude because of the weather seasons, while Dv15 increases in 4.2 °C (from 17.4 °C in winter to 21.6 °C in summer). Dv11 and Dv12 show a mean slurry temperature of 14.2 °C for winter and Dv13 of 19.7 °C for summer. These differences between slurry temperatures in the same monitoring period are affected by surrounding shadows, since there are more trees in the valleys, while there are just a few or none at all in the highlands. Slurry temperature is in a range of −1.3 to 2.5 °C in relation to the ambient temperature.

During the winter, the valley digesters that (unlike the highland digesters) do not carry any special adaptation to take advantage of the solar passive heating, reach similar slurry temperatures (15.3 °C) to those from the highlands (14.7 °C). However the winter mean ambient temperature is 8.5 °C higher in valleys than in the highlands. During the summer, valley digesters reach slurry temperatures of around 20 °C, which is more than 3 °C higher than at highland temperatures.

The thermal performance of other Andean valley digesters was reported by (Garfí et al., 2011b), but these digesters were adapted to cold climate such as the highland digesters (greenhouse and massive adobe walls), presenting slurry temperatures in the ranges of 16.3 to 20 °C, which is −1.2 to 2.2 °C above the ambient temperature, a very similar range to the one reported in this work for valley digesters without any special cold climate adaptation.

Biogas production and user ***behavior***

Three digesters were monitored in order to know the biogas production, but five biogas production profiles were identified since one of the systems is a two stage digester (each one is monitored separately), and in a second system the user changed the frequency and amount of load (see Table 3). Since each of the 5 profiles operates in valley conditions, data from a reported experimental digester (D90) has been also considered, to evaluate differences between regions.

Fig. 4 shows the accumulative biogas production for a two stage system (7.3 m^3 total liquid volume) which is fed with cow manure, in valley conditions, along with the days where the system was loaded, showing a scattered feeding frequency. This system installed in 2008, is loaded with 12.9 kg of fresh cow manure all 23% of the days, resulting in 118.2 days of HRT. Mean daily biogas production for the whole

Tamb (c°) ^{m}	ΔT (C°)^{2}	%CH_4	%CO_2	%Others gases	% Loading days	Manure when loaded (kg)^{3}	Daily mml (kg/day)^{4,m}	Biogas per day (m^3/day)^{5}	Real OLR (kg_{SV}/m^3/day)^{m}	SBP (m^3/kg_{SV})^{6,m}	BPR (m^3/m^3/day)^{6,m}	Real THR (days)^{m}
		47.8	44.8	7.4	<25							
		39.2	37.1	23.6	<25							
		44.6	39.6	15.8	<25							
9.1	7.8	50.0	40.8	9.2	<25							
6.5	8.1	46.7	35.7	17.6	<25							
6.5	8.3	49.8	36.8	13.4	<25							
8.6	8.0	47.2	39.1	13.7	73	2.36	1.7	0.08	0.26	0.23	0.06	125.0
7.7	8.1	46.5	39.1	14.4								
		59.3	24.1	16.6	25							
		52.1	36.3	11.6	25							
		50.4	30.7	18.9	25							
		48.4	28.5	23.1	25							
15.0	−0.2	56.0	20.3	23.7	25							
15.0	−1.3	50.7	27.2	21.6	25							
20.0	−0.3	49.6	23.7	17.1	23	56.16	12.9	0.85	0.18	0.45	0.08	118.2
					100	17.60	17.6	0.48	0.52	0.17	0.09	47.0
					51	24.46	12.4	0.45	0.37	0.23	0.09	85.4
	−0.6	52.4	27.3	18.9								
19.5	2.1	43.9	41.7	14.5	94	39.9	37.5	2.29	1.15	0.21	0.25	34.11
19.5	2.1	43.5	41.7	14.8	94	39.9	37.5	2.86	0.58	0.27	0.15	68.21

system (Dv13) is known and corresponds to 0.83 m^3/day (at local conditions).

Fig. 5 shows two different profiles for a unique one stage digester (3.65 m^3 liquid volume) fed with cow manure in the valley. The left figure explains the circumstance when the farmer loads the digester every day (100%) with the same amount of water (52.8 l) and manure (17.6 kg). The right figure corresponds to a fed schedule of only half of the days with 73.4 l of water and 24.5 kg of manure, decreasing the manure:water ratio from 1:3.4 to 1:2.5. Mean daily biogas production is provided for both profiles with 0.48 m^3/day for the first case and 0.45 m^3/day for the second one (at local conditions). This system was installed in 2011.

Fig. 6 shows the accumulative biogas production for the two stage systems (6.47 m^3 liquid volume for each stage), loaded with pig manure in the valleys, along with the days where the system was loaded. This system is fed with 39.9 kg of fresh pig manure 94% of the days. The digester was installed in 2010 and the main benefit expected from the user was to reduce the odor of fresh pig manure and to use the system as a waste water treatment system, without initial interest on the biogas or the bioslurry outcome. Once the system began to produce biogas and bioslurry the owner began to use these resources, but always like side products. Differentiated data for the first (Dv15a), the second stage and the total system (Dv15b) is presented. The slope represents the mean biogas production per day (at local conditions). In this circumstance it can be observed that the second stage provides only 20% of the biogas production for the whole system, while both stages have an equal volume. So when the HRT is doubled (and the system volume) from 34 to 68 days, the biogas production increases from 2.3 m^3/day to 2.9 m^3/day (at local conditions).

Biogas composition

Samples of biogas were collected from six digesters from each region. Results show that at cow manure fed digesters in the valleys, the CH_4 content is not significantly higher (with 52.4%, 3.9 sd) than in the highlands (46.5%, 3.7 sd), which are in the range of 43 to 67% of CH_4 as reported by Alvarez et al. (2006). For CO_2 content in biogas the results are 27.3% (5.3 sd) for valleys, and 39.1% (3.1 sd) for highlands, less than the 45.6% of CO_2 reported by Garfí et al. (2011b) and in the range of 37.3 to 40% reported by Ferrer et al. (2011) for Andean valleys. The presence of other gases is 18.9% (4.3 sd) in the valleys and 14.4% (5.4 sd) for the highland.

For pig manure fed digesters in the valleys, the results are: 43.7% for CH_4, 41.7% for CO_2 and 14.6% for the remaining gases. These results are very distant to the 74.4% of CH4 for the pig manure fed digester in tropical weather reported by Lansing et al. (2008), and closer to the 44.6% of CO_2 reported by Garfí et al. (2011b) from Andean valleys.

Characterization of digesters

Finally the digesters that were intensively monitored can be characterized by OLR, HRT, SBP and BPR, as shown in Table 3, where data is normalized to 1 atm and 0 °C. For valleys and cow manure fed digesters the mean real OLR varies from 0.18 to 0.52 kg_{SV}/m^3/day according to the % of days that the family loads the digester, being the designed OLR of 0.66 kg_{SV}/m^3/day. This leads to an SBP in a range of 0.17–0.45 m^3/kg_{SV} which is higher for lower OLRs. The BPR is very similar in the three cases of cow manure fed digesters moving in a range of 0.08–0.09 m^3/m^3/day. Compared with the reference highland cow fed digester D90 (Martí-Herrero et al., 2014b), with OLR 0.26 kg_{SV}/m^3/day, SBP 0.22 m^3/kg_{SV} and BPR 0.06 m^3/m^3/day, valley systems show a better performance. Other data reported from similar digesters and conditions in Andean valleys were the one from Garfí et al. (2011b) and Ferrer et al. (2011), that when normalized to 1 atm and 0 °C (Martí-Herrero et al., 2014b), turned out in OLR 0.22–0.34 kg_{SV}/m^3/day, SBP 0.30–0.3350 m^3/kg_{SV} and BPR 0.065–0.11 m^3/m^3/day, respectively. The results from the present study show that the mean real OLR in household digesters, has a wider range of OLR (feeding pattern) and SBP than those, in controlled conditions, reported in literature. On the other hand, the real BPR is in a narrow range with respect to previous literature results. Fig. 7 shows the SBP and BPR for valley cow manure fed digesters and demonstrates a good potential adjustment for SBP with negative exponent when increasing OLR, while a linear adjustment with a positive slope for the BPR is obtained. These fits agree with Alvarez and Lidén (2006) who, at laboratory scale and a wider range of OLRs of cow manure digesters, also show the same performance for SBP and BPR related to the OLR.

In the case of valley pig manure fed digesters, the characterization of both profiles indicates: 34 and 68 days of HRT, the mean real OLR is 1.15 and 0.58 kg_{SV}/m^3/day, the SBP is 0.31 and 0.38 m^3/kg_{SV}, and the BPR is 0.35 and 0.22 m^3/m^3/day, respectively. Since these values were estimated for a slurry temperature of 21.6 °C, they can be compared with those reported by Lansing et al. (2008) from a similar digester for tropical

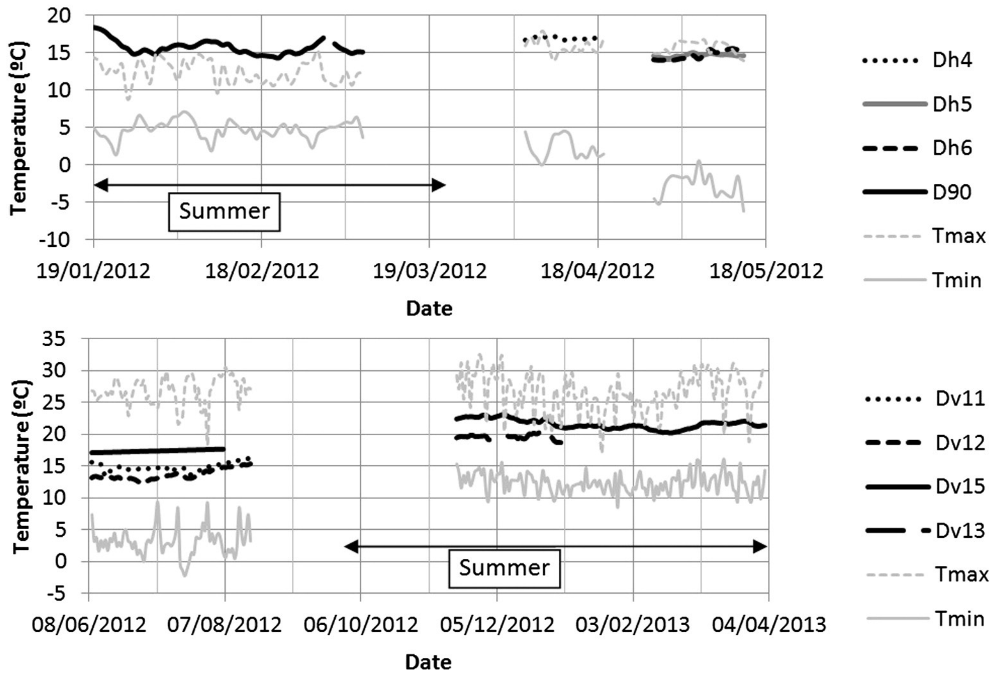

Fig. 3. Slurry temperatures for different digesters in the Bolivian Altiplano (top) and valleys (bottom), with daily maximum and minimum ambient temperatures.

conditions and a slurry temperature of 25.7 °C, reporting an OLR, SBP and BPR (normalized from original data to 1 atm and 0 °C) of 0.10 kg_{SV}/m^3/day, 0.88 kg_{SV}/m^3/day and 0.09 m^3/m^3/day respectively. When data from Lansing et al. (2008) is used to complete those numbers from valley pig manure fed digesters of the present research, the relation between SBP and BPR related to the OLR can be estimated (Fig. 7), finding similar performances to cow manure digesters and the ones reported by Alvarez and Lidén (2006).

At Fig. 7, it can be deduced that the increase in OLR is more sensitive in the BPR when the substrate is pig manure instead of cow manure. Furthermore, an increase on BPR implies less SBP, so it is to be expected that the quality of bioslurry decreases, or the efficiency of the waste water treatment system reduces.

Social analysis results

The outcome from the social analysis of indigenous Aymara families reveals that the use of biogas for cooking is not as successful as expected, since the families keep using wood and dry manure combined with LPG and biogas in their daily cooking activities. Interviews and observation indicate that even if biogas is available, families still prefer wood fire, as it accomplishes a double purpose, which is to heat the house at the same time as it provides cooking facilities. Heating the fire place and therefore the house also creates a special space, for daily social interaction within the families. These are aspects that economical, technical, and even other social analysis, do not consider, but are of great importance to the daily living and communication of the families.

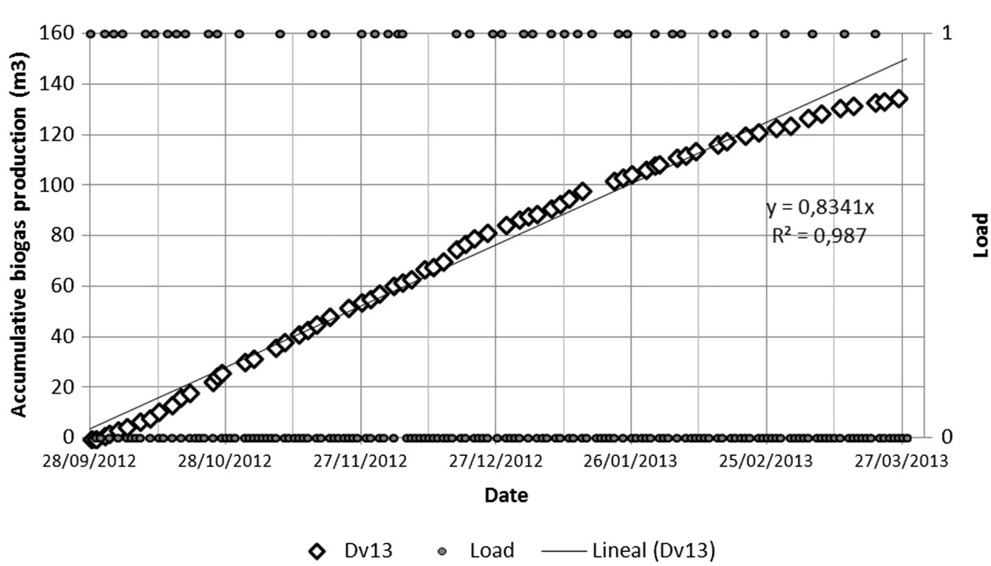

Fig. 4. Accumulative biogas production (at local conditions) for the two stage digester Dv13, with the loading days.

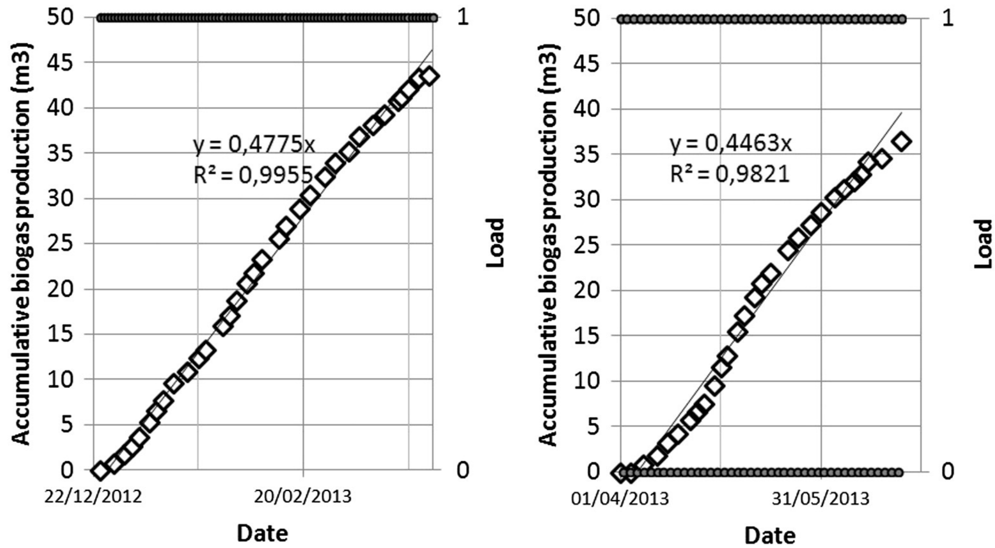

Fig. 5. Accumulative biogas production (at local conditions) for the single stage digester Dv14, with the loading days. Left: 100% days. Right: 51% days.

Furthermore, when the indigenous Aymara families were asked about their own ideas of poverty, none of them agreed with the MPI assessment. On the contrary they are proud of their land and animals, their freedom and their independence. When they were asked about what they value most in their lives and is most important for them, every single person mentioned nature, the cultivation of their fields and their food – even before mentioning family or religion. As water resources are scarce in the region, improvements in the availability of water for agricultural purposes and irrigation systems were brought up as the most important actual matter. In this context, energy was also mentioned, to command a possible water systems distribution and ease the usually manual dispersion for watering the fields. Further aspirations focused on improved mixtures of fertilizers, pesticides and frost recovery mixtures.

Concerning the areas of the MPI, the need for electricity was mentioned by the indigenous Aymara families. While the older generation was mainly focused about energy in the context of irrigation systems, the younger generation also wanted electricity to power electronic devices and charge mobile phones. The need for other cooking fuels besides fire wood was mentioned too, mainly by women, but not as a main priority. Other indicators of the MPI as the living standard criteria or the health sector were not mentioned by the families at all (improved sanitation, safe drinking water or house flooring). The only issue that was strongly highlighted by all the people interviewed, apart from agricultural improvements, was the need for a better and more suitable school system that considers their culture and language and focuses more on agricultural knowledge.

The responses from users of intense and partially monitored digesters about type of cooking and fuel employed can be found in Table 4. Highland families use more diversified fuels. In three cases wood and/or cow dry manure appear in the answers, and in other three families they only use clean fuels such as LPG and biogas. In the valleys, five families do not mention biogas as a cooking fuel alternative, they just combine LPG and fuel wood, while the remaining three families just cook with clean fuels.

When Aymara families were asked about their satisfaction with the digester, they revealed that they liked the bioslurry, more than the biogas. They comment that the bioslurry protects the crops from frost, also that it improves the recovery of them from frost damage, and increases crop production, as earlier highlighted in previous publications like Martí-Herrero et al. (2014a) and Garfí et al. (2011a).

The digesters are usually promoted as a renewable energy technology focused in biogas, while the production of the fertilizer is seen as a mere 'side product' (Martí-Herrero et al., 2014a). In this research, the bioslurry side product turns out to be of great significance in the Andean background.

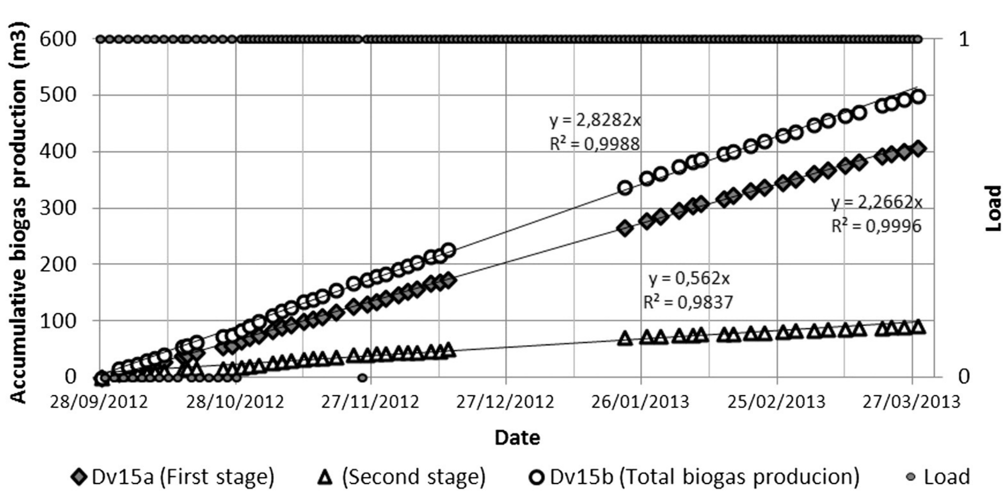

Fig. 6. Accumulative biogas production (at local conditions) for the two stage digester Dv15, with the loading days.

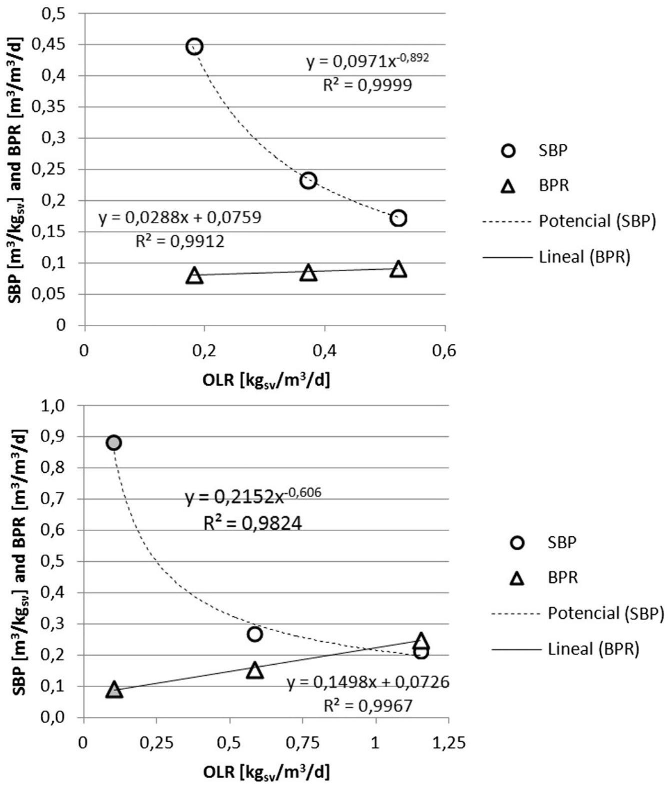

Fig. 7. SBP and BPR (normalized to 1 atm and 0 °C). Top: for the valley cow manure fed digesters (Dv13, Dv14a and Dv14b). Bottom: For the valley pig manure fed digester (Dv15a and Dv15b) and data from Lansing et al. (2008) that was normalized to 1 atm and 0 °C, it appear as a fill gray symbol.

Table 4
Data from highland and valleys family user of digesters that have been monitored.

No	Location	Year of installation	Family size	No. of heads (only cows)	Cooking[a]
Dh1	Highland	2010	4	<10	LPG/BG/CDM/W
Dh2	Highland	2010	4	<10	LPG/BG/W
Dh3	Highland	2010	4	<10	LPG/BG/CDM/W
Dh4	Highland	2010	10	<10	LPG/BG
Dh5	Highland	2010	12	<10	LPG/BG
Dh6	Highland	2010	3	<10	LPG/BG
Dv7	Valley	2011	5	≥10	LPG/W
Dv8	Valley	2011	10	<10	LPG/W
Dv9	Valley	2011	3	<10	LPG/W
Dv10	Valley	2011	12	<10	LPG/W
Dv11	Valley	2011	3	≥10	LPG/W
Dv12	Valley	2011	8	<10	LPG/BG
Dv13	Valley	2008	8	<10	LPG/BG
Dv14	Valley	2011	2	<10	LPG/BG
Dv15	Valley	2010	4	100[b]	LPG/BG

[a] LPG: Liquefied petroleum gas;W: Wood; BG: Biogas; CDM: Cow dry manure.
[b] Number of pigs.

Social and technical discussion

Digesters monitored in this study tend to be under loaded by users in highland and Andean valleys, because families do not feed the digester every day despite having sufficient manure and water availability. Though in the case of the pig manure fed digester (Dv15) it is different, since the family is using the digester as a waste water treatment system more than as a biogas/bioslurry generator. This system is producing more than 2.8 m^3/day of biogas, which is more than what a typical family needs for three cooking periods per day, so the family is exploring to use the excess of biogas in heating the piglets. Furthermore, the family is using the bioslurry in a nearby crop field. In the case of Dv14, a valley cow manure fed digester, results show that the load schedule can vary significantly during the year. This issue can be related to the agricultural calendar of this region. In winter, less bioslurry is needed for crop production, leading to a load frequency reduction. This particular case demonstrates how the users reduce the frequency of load but tries to compensate it by increasing the amount of manure loaded from 17.6 kg every day (100% days) to 24.5 kg almost every 2 days (51% days), obtaining good results since the biogas production only varies from 0.478 m^3/day to 0.446 m^3/day. This family is composed of only two members, so the low amount of biogas can partially supply their cooking fuel needs, and the remaining needs are satisfied with LPG. Moreover this is a good example to show how reducing the OLR, and increasing the HRT and SBP, can maintain similar BPR, as demonstrated in Fig. 7.

Cow manure two stage digester (Dv13) in the valley seems to be employed in a similar way, since the user loads only 23% of the days but with 56.2 kg of fresh manure. The Dv13 system is designed for 40 kg/day, so again, the user reduces the frequency of load but increases the amount of load, trying to compensate or maintain the biogas production. In this case the user produces 834 m^3/day of biogas, which he combines with LPG to cover the fuel needs for daily cooking for his 8 member family. Farmers know that increasing the HRT, the quality of bioslurry will be higher, and this is correlated to a higher SBP that leads to a better degradation of the manure inside the digester.

During the winter period the partial monitored digesters have less than 25% of load frequency in the highlands and the valleys, with no information about the summer period. This behavior can be related to the little use of bioslurry for crop production during the cold winter season. Whereas manure and water availability to feed the digester throughout the year, that could be an issue, does not vary significantly, so the irregular load frequency should be related to other reasons in the case of these families.

The main question is: Why the families do not produce more biogas to replace the LPG, despite not needing that much bioslurry? There are two important reasons to answer this query, the first is related to the government energy policy and the second one to Bolivian culture and traditions. In Bolivia, LPG is subsided by the government, a 15 l LPG tank costs 3.26 US$, and it is widely distributed throughout the rural area. The second reason is to understand that further than providing the LPG user with a clean cooking fuel, it also grants the family a higher social status in comparison to those families who still use wood or dry cow manure as a cooking fuel. The families who took part in this study, combined wood or dry manure with LPG, (when able) for cooking. Once they installed a digester in their households, the biogas displaced the consumption of wood or dry manure, leaving these smoky fuels for special cultural meals, combining LPG and biogas for their daily cooking, and improving in this way their social status within the community.

As highlighted in the social analysis conducted among indigenous Aymara users, the main product of the household digesters is related to agriculture and farm activities, while the energy gained in form of biogas for cooking is less appreciated. In other words, at present it is the bioslurry, and not the biogas that plays the key role. It determines the use and performance of the digester. Fostered by the fact that LPG is cheap and accessible, the digester is seen as bioslurry producer rather than as an energy generator. In order to strengthen the use and interest on biogas, uses related to farm activities could be enhanced as heating the stables or pigpen, heating the water for the cows, or using biogas for sanitizing milking appliances.

Finally it is important to understand, that users' needs and expectations define the performance of the digester. This can vary from a waste water treatment system with a high frequency loading rate, to the minor importance of the biogas production considered just as replacement of a cooking fuel, or a fertilizer producer, integrating the system to the agricultural calendar. Identifying users' needs is determinant for the digester management. Therefore digesters' design and policies should consider users' needs, traditions, and future expectations.

Conclusions

Household low cost tubular digesters adapted to cold climate have a similar slurry temperature in winter to those of low cost digesters installed in the valleys with warmer climatic conditions (surrounding 14.5 °C), although in summer the difference in slurry temperature grows, reaching 20 °C in the valleys, which is almost 3 °C above the temperature of the highland digesters. This finding leads us to consider the introduction of passive solar heating strategies like the ones for the highland to the valley systems. The characterization of the digesters show what happens when the OLR is increased, the SBP is reduced but the BPR keeps similar values, indicating that tubular digesters in valley regions have a constant BPR, which is around 0.08–0.09 m^3/m^3/day (at normal conditions: 1 atm, 0 °C) independently of load schedule for OLR, in a range of 0.18–0.52 kg_{SV}/m^3/day.

User behavior at the household level restricts the performance of the digester depending on its own needs, taking into account that, in a subsidized LPG country, farmer families are more focused in bioslurry production according to the agricultural calendar, or on the waste water treatment system that has a constant and high load frequency.

Finally, in this research, the poverty concept is perceived in a different way by those people that the MPI identifies as poor, so the involved families transform and adapt a typical energy poverty reduction technology to a tool that improves agricultural productivity, which is their main aspiration and need.

Acknowledgments

Financial support to carry out this research was provided by Hivos, with the collaboration of PROSUCO, the Endev-Bolivia Program of the GIZ, the Caribbean and Latin American Biodigesters Net (RedBioLAC) and the Research Center of Biodigesters, Biogas and Biol (CIB3, Bolivia). Also thanks to Georg Gruenberg (BOKU) and Michael Sturm (ITT) as local thesis tutors of Linda and Maria. Jaime Martí-Herrero is thankful to the Prometeo Project of the Secretariat for Higher Education, Science, Technology and Innovation of the Republic of Ecuador that funded part of his work. The authors wish to acknowledge the revision of the document by Mike Baker and Samay Schütt. Suggestions provided by three anonymous reviewers improved this paper.

References

Alkire S, Santos ME. Acute multidimensional poverty: a new index for developing countries. Working Paper 38. Oxford Poverty and Human Development Initiative, University of Oxford; 2010. [cited January 2015, Available from http://www.ophi.org.uk/wp-content/uploads/ophi-wp38.pdf].
Alvarez R, Villca S, Lidén Gunnar. Biogas production from llama and cow manure at high altitude. Biomass Bioenergy 2006;30:66–75.
Arthur R, Baidoo MF, Antwi E. Biogas as a potential renewable energy source: a Ghanaian case study. Renew Energy 2011;36:1510–6.
Bond T, Templeton MR. History and future of domestic biogas plants in the developing world. Energy Sustain Dev 2011;15:347–54.
Bonten LTC, Zwart KB, Rietra RPJJ, Postma R, de Haas MJG. Bio-slurry as fertilizer: is bioslurry from household digesters a better fertilizer than manure? A literature review. Alterra report 2519. Wageningen, Alterra: Wageningen UR (University & Research centre); 2014 [SNV. ISSN 1566–7197, cited January 2015, Available from http://www.snvworld.org/en/download/publications/alterra_report_2519_bioslurry.pdf].
Botero RB, Preston TR. Biodigestor de bajo costo para la producción de combustible y fertilizante a partir de excretas: manual para su instalación, operación y utilización. Cali, Colombia: CIPAV; 1987 [20 pp., cited January 2015, Available from http://www.utafoundation.org/publications/botero%26preston.pdf].
Bui Xuan An, Ngo Van Man, Duong Nguyen Khang, Nguyen Duc Anh, Preston TR. Installation and performance of low-cost polyethylene tube biodigesters on small scale farms in Vietnam. Proc. National Seminar-workshop in sustainable Livestock Prod. on local feed resources. Agric. Pub. House Ho Chi Minh; 1994. p. 95–103.
Chen L, Zhao L, Ren C, Wang F. The progress and prospects of rural biogas production in China. Energy Policy 2012;51:58–63.
Clesceri LS, Greeberg AE, Eaton AD. Standard methods for the examination of water and wastewater. 20th ed. Washington, DC, USA: American Public Health Association (APHA); 2000.
de Groot L, Bogdanski A. Bioslurry = brown gold? A review of scientific literature on the co-product of biogas production. FAO 978-92-5-107929-4; 2013 [cited January 2015, Available from http://www.fao.org/docrep/018/i3441e/i3441e.pdf].
Ferrer I, Garfí M, Uggetti E, Ferrer-Martí L, Calderon A, Velo E. Biogas production in low-cost household digesters at the Peruvian Andes. Biomass Bioenergy 2011;35:1166–674.
Garfí M, Gelman P, Comas J, Carrasco W, Ferrer I. Agricultural reuse of the digestate from low-cost tubular digesters in rural Andean communities. Waste Manag 2011a;31:2584–9.
Garfí M, Ferrer-Martí L, Irene Perez I, Flotats X, Ferrer I. Codigestion of cow and guinea pig manure in low-cost tubular digesters at high altitude. Ecol Eng 2011b;37:2066–70.
Garfí M, Ferrer-Martí L, Velo E, Ferrer I. Evaluating benefits of low-cost household digesters for rural Andean communities. Renew Sustain Energy Rev 2012;16:575–81.
Garfí M, Cadena E, Pérez I, Ferrer I. Technical, economic and environmental assessment of household biogas digesters for rural communities. Renew Energy 2014;62:313–8.
Ghimire PC. SNV supported domestic biogas programmes in Asia and Africa. Renew Energy 2013;49:90–4.
International Energy Agency. World Energy Outlook (WEO) 2012. cited January 2015, Available from: http://www.iea.org/publications/freepublications/publication/English.pdf, 2012.
Kottak C. Mirror for humanity. New York: McGraw-Hill 978-0-07-803490-9; 2006. p. 47.
Lansing S, Botero R, Martin JF. Waste treatment and biogas quality in small-scale agricultural digesters. Bioresour Technol 2008;99(13):5881–90.
Martí-Herrero J. Transfer of low-cost plastic biodigester technology at household level in Bolivia. Livest. Res. Rural. Dev. 2007;19(12). [Article #192, cited January 2015, Available from http://www.lrrd.org/lrrd19/12/mart19192.htm].
Martí-Herrero J. Biodigestores Familiares. Guía de diseño y manual de instalación. La Paz, Bolivia: Cooperación Técnica Alemana-GTZ 978-99954-0-339-3; 2008 [cited January 2015, Available from http://books.google.es/books?id=TsbrdcmKGKoC].
Martí-Herrero J. Reduced hydraulic retention times in low-cost tubular digesters: two issues. Biomass Bioenergy 2011;35(10):4481–4.
Martí-Herrero J, Cipriano J. Design methodology for low cost tubular digesters. Bioresour Technol 2012;108:21–7.
Martí-Herrero J, Chipana M, Cuevas C, Paco G, Serrano V, Zymla B, et al. Low cost tubular digesters as appropriate technology for widespread application: results and lessons learned from Bolivia. Renew Energy 2014a;71:156–65.
Martí-Herrero J, Alvarez R, Rojas MR, Aliaga L, Céspedes R, Carbonell J. Improvement through low cost biofilm carrier in anaerobic tubular digestion in cold climate regions. Bioresour Technol 2014b;167:87–93.
Mwirigi JW, Makenzi PM, Ochola Wo. 'Socio-economic constraints to adoption and sustainability of biogas technology by farmers in Nakuru Districts, Kenya. Energy Sustain Dev 2009;13:106–15.
Nzila C, Dewulf J, Spanjers H, Tuigong D, Kiriamiti H, van Langenhove H. Multi criteria sustainability assessment of biogas production in Kenya. Appl Energy 2012;93:496–506.
Perrigault T, Weatherford V, Martí-Herrero J, Poggio D. Towards thermal design optimization of tubular digesters in cold climates: a heat transfer model. Bioresour Technol 2012;124:259–68.
Poggio D, Ferrer I, Batet Ll, Velo E. Adaptation of plastic tubular digesters to cold climates. Livest Res Rural Dev 2009;21(9). [cited January 2015, Available from http://www.lrrd.org/lrrd21/9/pogg21152.htm].
Pound B, Bordas F, Preston TR. Characteristics of production and function of a 15 cubic metre Red-Mud PVC biogas digester. Trop Anim Prod 1981;6:146–53.
UNDP. Human development reports. Statistics. Indices and data. Multiple Poverty Index. cited January 2014, Available from http://hdr.undp.org/en/statistics/mpi/, 2010.
van Groenendaal W, Gehua W. Microanalysis of the benefits of China's family-size bio-digesters. Energy 2010;35:4457–66.
Walekhwa PN, Mugisha J, Drake L. Biogas energy from family-sized digesters in Uganda: critical factors and policy implications. Energy Policy 2009;37:2754–62.
Warnars L, Oppenoorth H. Bioslurry: a supreme fertiliser. A study on bioslurry results and uses. Hivos 978-90-70435-07-3; 2014 [cited January 2014, Available from https://www.hivos.org/sites/default/files/bioslurry_book.pdf].
Yiridoe E, Gordon R, Brown B. Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. Energy Sustain Dev 2009;13:106–15.